STANFORD RESEARCH INSTITUTE

MENLO PARK, CALIFORNIA

SRI

CR 86169

MEMORANDUM 8

DEEP-SPACE OPTICAL COMMUNICATION SYSTEMS

Distribution:

Baron
Kamphoefner
Merritt
Peschon
Larson
Meier
Fraser
Dressler
Keckler
Ratner
Luenberger
Eikelman

Prepared by:

Edward C. Fraser
Robert M. Dressler

December 30, 1966

Project ESU 5578

CONTENTS

LIST OF ILLUSTRATIONS iii

LIST OF TABLES iii

I INTRODUCTION 1

II SYSTEM CONSIDERATIONS 4

A. Configurations 4

1. Open Loop 4
2. Cooperative 6
3. Closed Loop 8

B. Environment 11

1. Earth's Atmosphere 12
2. Free Space 19

C. Implementation 20

1. State-of-the-Art Techniques 21
2. Novel Techniques 23

III SYSTEM EVALUATION 25

A. Structure of Earth-Based Terminal 25

B. Modeling of Tracking-System Components 29

IV CONCLUSIONS 31

REFERENCES 33

Appendix A--NUMERICAL EXAMPLE 35

Appendix B--GLOSSARY OF TERMS 44

ILLUSTRATIONS

Fig. 1	Open-Loop Communication System--One Way.	5
Fig. 2	Cooperative Communication System--One of Two Identical Terminals.	7
Fig. 3	Closed-Loop Communication System (Arrayed Receiver Technique).	9
Fig. 4	Atmospheric Transmittance.	13
Fig. 5	Beam Pattern of a Ruby Laser at 11.6 km.	14
Fig. 6	Effect of Atmospheric Scintillation-- 3-Inch Aperture Diameter	15
Fig. 7	Structure of Earth-Based Terminal.	26

TABLES

Table I	Mean Refraction.	16

I INTRODUCTION

The advent of lasers as extremely-narrow-beamwidth high-power light sources has made viable the consideration of light as the carrier for high-data-rate communication between the earth and a deep-space probe. Additionally, the high frequency of light (10^{14} to 10^{15} Hz) allows very-broad-band modulation (on the order of 10^9 Hz) while maintaining a ratio of channel bandwidth to carrier frequency typically less than 10^{-4}, and thus avoiding one of the factors that limits the capacity of conventional RF communication channels. A second feature of the narrow beamwidths is the greatly increased resolution and accuracy with which the tracking angles to a distant object can be measured. This considerably upgraded tracking data will permit much more accurate and rapid orbit determination, particularly for vehicles near earth, than has been possible with conventional tracking techniques.

The extremely narrow transmitter beamwidths and receiver fields of view (in the order of 0.1 arc second or less) that are necessary to realize efficient operation of an optical communication system dictate that the control systems employed to point the transmitters and receivers be capable of producing an unprecedented level of accuracy and precision. To achieve the required levels of accuracy and precision, the entire system, from concept and configuration to detailed specification of optical, mechanical, and electronic components, must be designed with this high-precision goal in mind. As a first step in that direction, this memorandum presents the results of a preliminary investigation into the questions of how an optical communication system should be designed, how the atmospheric and space environment will affect the operation of the communication system, and what are the properties of presently available and anticipated devices and techniques that will be needed to realize some of the required operations.

The results of these investigations are presented in two parts. Section II discusses those considerations that are common to any optical communication system. The mode of operation as well as the relative advantages and disadvantages of the three basic system configurations--open-loop, cooperative, and closed-loop--are described. The optical properties of the propagation environment, including both "free" space and the earth's atmosphere, are described in detail since this data will be needed in formulating a model of the disturbances experienced by a system of any design. State-of-the-art techniques and devices are assessed as to their immediate applicability to a high-precision system, and those areas where further development work is required to fully exploit optical system capabilities are pointed out.

In Sec. III the cooperative system configuration has been selected for a detailed study and simulation to accurately evaluate potential system performance. This simulation represents a natural evolution of the research on high-precision antenna tracking and the optimal estimation and control program that was developed and is reported in Memorandum 7.[1*] In order to implement the simulation, the detailed sturcture of the ground-based terminal of a cooperative communication system is specified, and all of the components that are included in the design are identified. In a sense, a "list of equipment" is enumerated, whose properties must be modeled and included in the simulation. While the specific equations and numerical parameter values are relegated to a companion memorandum, a summary of the techniques to be used is presented.

To demonstrate that even in the early stages of their development optical systems can provide communication channel capacities several orders of magnitude greater than is presently achievable by radio frequency techniques, a numerical example is presented in Appendix A. In this appendix the up-link and down-link channel capacities are calculated, assuming parameter values that are either now within the state of the art, or will be within the next two or three years.

---

*References are listed at the end of the text.

A glossary of terms and definitions is included as Appendix B to ensure precise interpretation of the terminology used, since many of the terms have acquired more than one meaning as a result of their use by several disciplines.

II SYSTEM CONSIDERATIONS

A. Configurations

Although one can envision any number of ramifications of the configuration of the pointing systems to be used in a deep-space communication system, there appear to be three distinct classes of system operation. These are termed open loop, cooperative, and closed loop, and are distinguished by the amount of tracking information gathered and exchanged by the two terminals and the frequency with which this exchange occurs. The properties of these three configurations, together with the relative advantages and disadvantages of each are examined in the following sections. The discussion is limited to the normal operational mode; the problems associated with an acquisition mode are mentioned only when a considerable departure from the normal mode is required in order to accomplish acquisition.

1. Open Loop

Open-loop pointing of the terminals of a deep-space communication system is the most simple and straightforward technique of those to be considered. In such a system the pointing of the transmitting and receiving terminals is done solely on the basis of computed pointing angles, the computations being based upon *a priori* knowledge of the spacecraft dynamics and the relevant celestial mechanics. Tracking data available from tracking systems such as the coherent-Doppler system presently used on deep-space missions can be used to update and correct the pointing angle computations. The structure of an open-loop system is illustrated in the block diagram of Fig. 1.

The pointing angles must be computed with respect to a fixed frame of reference. The earth-based terminal would use the earth itself as a reference frame and compute pointing angles relative to reference directions fixed at the terminal site. The on-board terminal, however, does not have such a built-in reference frame and would have to employ a minimum of two star sights in order to establish a frame of reference.

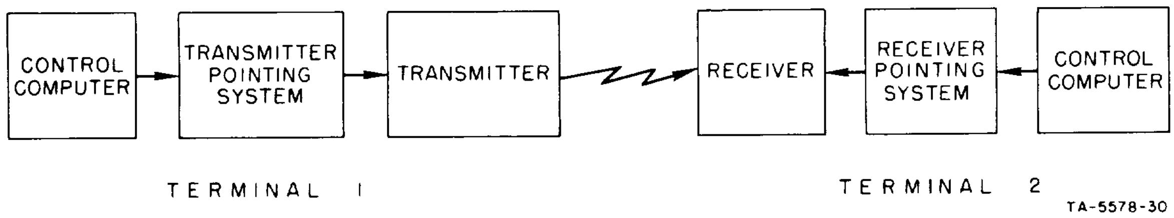


FIG. 1 OPEN-LOOP COMMUNICATION SYSTEM — ONE WAY

Operation in the open-loop mode implies that the two terminals operate entirely independent of each other. However, to minimize the computational capability required onboard the spacecraft, it will be desirable to store in the spacecraft computer a pointing-angle computation algorithm that is valid for only a short time (of the order of several days, once the spacecraft has left the vicinity of the earth). This algorithm would be periodically replaced by transmission to the spacecraft of an updated algorithm computed on the earth. Furthermore, compensation for errors resulting from an inaccurate trajectory model, and detected by other tracking systems, can be included in the updated algorithms. Since there is no requirement that this information be transferred rapidly, a relatively-low-bandwidth RF communication channel would serve this purpose.

The most significant advantage of an open-loop system configuration is that a minimum of equipment and equipment complexity is required for system operation. In particular, no optical up-link is required if high-data-rate transmission is to be only from the spacecraft to the earth. In addition, no scanning or angle-detection capability need be built into the optical receivers since in the open-loop configuration the angle of arrival of the incoming signal is not measured. A second advantage of the open-loop configuration is that the question of acquisition does not arise. Once the star trackers have provided the spacecraft with a reference frame, acquisition depends only on the accuracy of the computed pointing angles and the pointing system.

A significant disadvantage of the open-loop configuration is that it is incapable of automatically compensating for pointing errors or disturbances, or for discrepancies between the computed pointing angles and those required to accomplish optimum optical beam pointing. Thus, to ensure system operation the optical beamwidth must be made considerably larger than would be required in other systems. Therefore, the communication channel resulting from an open-loop configuration will either have a significantly lower bandwidth or require considerably higher transmitter power to accomplish the same communication performance achievable by other system configurations. A second disadvantage is that the pointing direction of the transmitted beam from the spacecraft does not necessarily lie near the reference directions as defined by the star trackers. Therefore, advantage cannot be taken of the small angle and differential beam-steering techniques to obtain higher beam-pointing accuracy than can be achieved by conventional methods. These techniques are more fully discussed in Sec. II-C.

2. Cooperative

The distinguishing feature of a cooperative configuration is that each terminal has an optical transmitter whose beam is used as an aiming point by the receiver of the other terminal. Thus, one of the two required reference directions for each of the terminals is provided by the line of sight between the two terminals. The receivers are each equipped to track the direction of the incoming beam and thereby maintain the receiver optical axis aligned with the line of sight. This eliminates the necessity for accurately computing receiver pointing angles since the active tracking automatically compensates for small errors and disturbances. The configuration of one terminal of a cooperative optical communication system is illustrated in the block diagram of Fig. 2.

The incoming beam provides only one of the two required references; therefore a second reference direction must still be obtained at each of the terminals. For the ground-based terminal a reference direction fixed with respect to the earth is sufficient. For the onboard terminal one star tracker will still be required

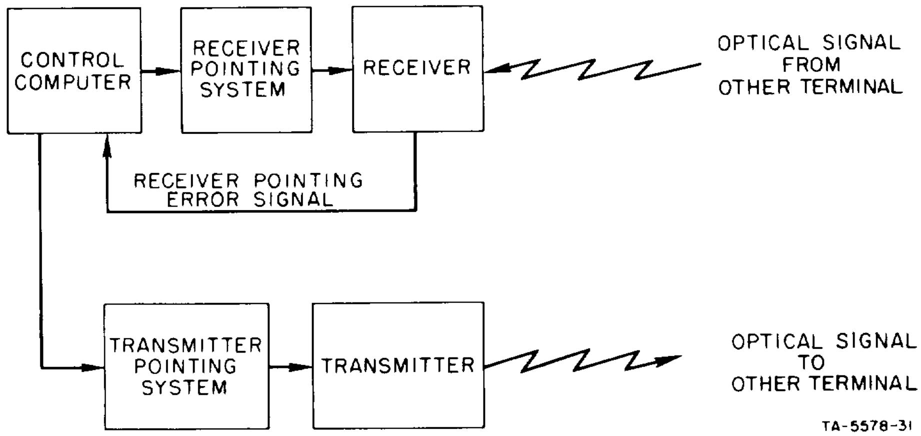


FIG. 2 COOPERATIVE COMMUNICATION SYSTEM — ONE OF TWO IDENTICAL TERMINALS

to provide the second reference direction. Since the spacecraft and the line of sight between the spacecraft and earth will lie generally within the ecliptic plane, it would be advantageous if this star tracker were locked onto a star lying near a line perpendicular to the ecliptic plane and intercepting the ecliptic plane somewhere within the earth's orbit.

The cooperative configuration provides a complete two-way communication system; hence the optical up-link can be used to communicate to the spacecraft computer updated pointing-angle information obtained on the ground.

The paramount advantage of a cooperative system configuration is that it permits the use of a smaller beamwidth and field of view than are possible with open-loop techniques. As a result, higher signal-to-noise ratios--or correspondingly greater channel bandwidth--can be expected for the same transmitter power level. A second advantage is the fact that active tracking of the incoming signal permits detection and compensation of disturbances to the spacecraft or deviation of the spacecraft from its anticipated path. A third advantage of the cooperative technique results from the fact that the optical communication receiver, by sighting on the other terminal's transmitter, establishes one of the reference directions, thus eliminating one optical system. In addition, since the angle between the receiver direction and transmitter pointing direction will be small, the same optical system can be used for both. Furthermore, the small angular difference permits the use of differential beam steering and small-angle techniques, which enhance beam-steering accuracy. A fourth advantage is that the computations required to generate offset pointing angles, as opposed to absolute pointing angles, are simpler, and the accuracy requirements are somewhat less stringent, resulting in a reduced requirement for computational capability, particularly at the spacecraft terminal. Finally, since this is a two-way communication system, the optical up-link can be used for transmitting pointing data, thus eliminating the need of a separate communication system for this purpose.

The primary disadvantage of a cooperative communication system, that employs narrow beamwidths and fields of view, is the problem of initial acquisition. It may be necessary to incorporate into the system the capability for broadening the transmitter beamwidth and receiver field of view in order to accomplish initial acquisition of each terminal by the other. Alternatively, a pre-programmed search may be used to accomplish acquisition, but this too implies increased system complexity and possible decrease in system reliability. A second disadvantage is the amount of equipment and its increased sophistication as compared to an open-loop system. At first look, this increase of system size and complexity would appear to reduce the overall system reliability. However, this reduction may be more than compensated by the enhanced performance achievable using the cooperative techniques.

3. <u>Closed Loop</u>

In this system, pointing errors of the transmitter at one terminal are sensed by the receiver of the second terminal, and pointing-error information is relayed back to the first transmitter for use in correcting the pointing error. The same procedure is followed for correcting pointing errors of the second transmitter. Two techniques have been suggested for detection of transmitter pointing errors by the receiver. In the first, the transmitted beam would be scanned over a small angle about the nominal direction of transmission. At the same time, a temporal modulation that is uniquely related to the spatial scan pattern would be applied to the transmitted beam in addition to the normal modulation required by the communication function. By detecting the beam modulation the receiver would be able to compute the corrections necessary to center the transmitter beam on the receiver. This information is then relayed back to the transmitter. An alternative method, which is only feasible for the earth-based terminal, is to employ an array of receivers. The transmitter pointing error is indicated by which receiver in the array has the largest signal relative to the primary receiving location. The structure of an earth-based receiving terminal for the closed-loop configuration is illustrated in Fig. 3.

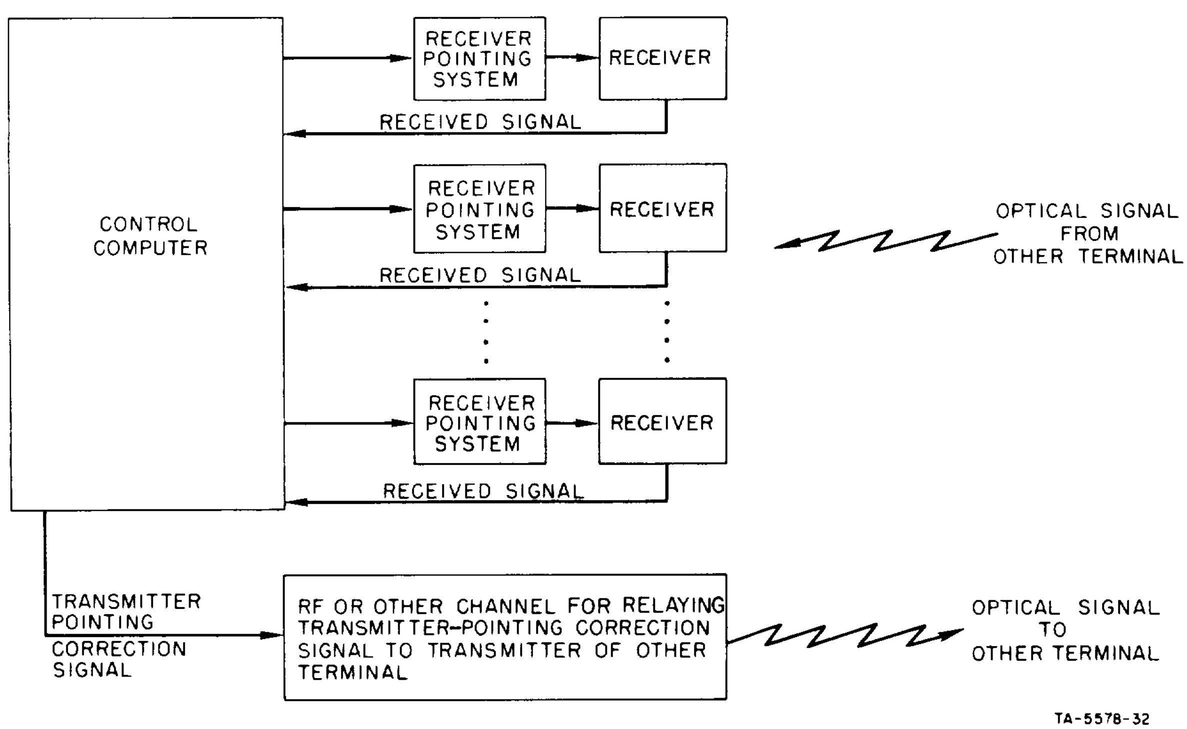


FIG. 3 CLOSED-LOOP COMMUNICATION SYSTEM (Arrayed Receiver Technique)

In the case of a beam-modulation technique a reference frame is inherent in the relationship of the temporal beam modulation to the spatial scan pattern. Since this reference frame is both generated and used, by each terminal independently, for pointing-error correction, no other reference frame is required during normal operation. For initial acquisition, however, means for establishing the location of the earth will be necessary, but this requirement can be satisfied by equipment much less complex than that needed to establish an accurate reference frame. Similarly, a reference frame is inherent in the receiver array, but this reference frame is not available onboard the spacecraft. Therefore, the spacecraft must include mechanisms for establishing the two required reference directions.

There are two principal advantages to the closed-loop system configuration. First, the operation of the system does not require accurate determination of direction, and in one case does not require directional reference at all except during the acquisition phase. Secondly, this technique in principle requires a minimum computational capability for the control of the pointing systems. However, practical considerations, as pointed out below, demand considerable computational capability in order to render the system workable.

The overriding problem of the closed-loop system configuration is the propagation or transit time between the two terminals. For missions to other nearby planets within our solar system, this transit time can be as much as ten minutes or more each way. As a result, the beam-steering control loop contains an effective transport delay of 20 minutes or more. This property poses serious stability problems if the control system is designed on the basis of conventional closed-loop servomechanism theory.[2] On the other hand, if the techniques of modern control theory are employed, which involve a dynamic model of the components of the system, correction of delayed-time operation of this model by the delayed measurement data, and estimation (prediction) of present system state from this model to derive appropriate control actions, then considerable computational capability will be required both on the ground and onboard the spacecraft.[3] Even so, the system will be incapable of compensating for any disturbance effects occurring on a time scale shorter than the round-trip transit time. The effects of high-frequency disturbances (high frequency here means greater than one cycle per hour) must still be handled on an essentially open-loop basis. A second disadvantage involves the methods by which the receiver detects transmitter pointing errors. In the case of beam modulation and scanning, the scanning will result in some reduction in the achievable signal-to-noise ratio, while the introduction of a characteristic modulation will absorb some of the system bandwidth that might otherwise be used for communication. Both of these effects are undesirable from a communication point of view. On the other hand, the use of an array of receiving points is limited to the down-link only. One final disadvantage of a closed-loop configuration is that it requires tracking information to be transmitted continuously both from the ground to the spacecraft and conversely. Since the communication channels must be used for purposes other than just pointing information, this implies the necessity for some form of continuous multiplexing and operation, and the attendant added system complexity.

B. Environment

Regardless of the configuration chosen for a deep-space optical communication system, it will have to operate within the limitations imposed by the environment existing along the propagation path. Since the properties of the environment are common to all system configurations, it is appropriate that they be discussed in detail in this section.

For a communication system that includes the earth's atmosphere within the propagation path, the predominant disturbances experienced will be due to atmospheric effects. If, on the other hand, both terminals are located outside the earth's atmosphere, then much smaller beam disturbances, due to the propagation properties of "free" space will be encountered.

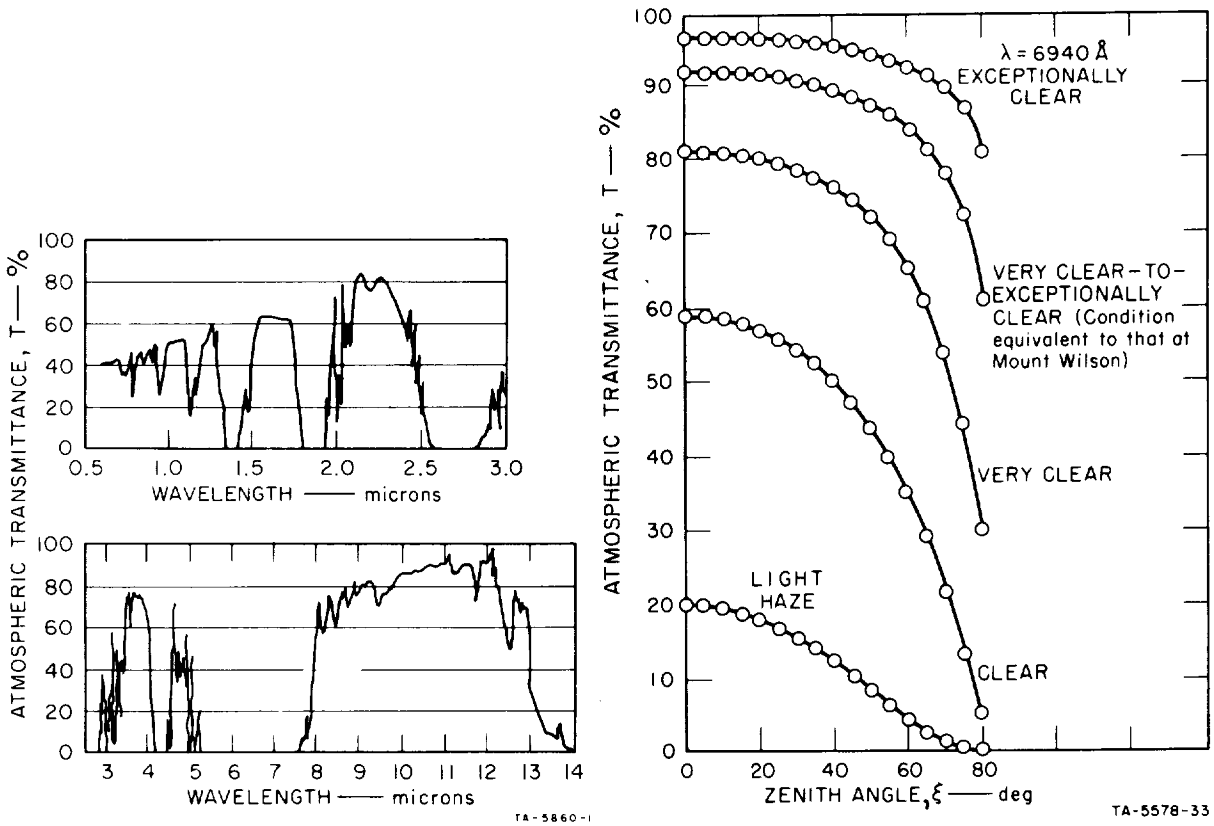
1. Earth's Atmosphere

The earth's atmosphere exhibits four effects upon the transmission of light: attenuation, scintillation, refraction, and image excursion. Attenuation is the reduction of signal intensity as the light beam traverses the atmosphere. This reduction is due to several phenomena including molecular absorption of photons, molecular scattering, and particulate and aerosol scattering. The extent of atmospheric attenuation is dependent upon the atmospheric condition (weather), and it changes as a relatively slow function of time. For tracking or communication purposes the attenuation effect of the atmosphere can be considered as a steady-state signal reduction. Typical values of atmospheric transmittance* as a function of wavelength and also of weather conditions are shown in Fig. 4.[4,5]

Scintillation is the relatively rapid variation of signal amplitude and is most commonly observed as the twinkling of stars or other distant lights viewed at night. Scintillation is the result of the turbulent mixing of volumes of air with differing indices of refraction. The effect is that the atmospheric path appears as a distribution of lenses, prisms, and refractive interfaces that tend to break up an otherwise homogeneous light beam into areas of relatively high signal intensity and adjacent areas of relative darkness. As this pattern of bright and dark areas moves across the aperture of an optical receiver, the effect is observed as a rapid variation in the signal amplitude. The extent of atmospheric-induced scintillation is illustrated in Fig. 5, which is a photograph

---

*Atmospheric transmittance is defined as the ratio of the power density at the earth's surface of a signal from a distant source after it has passed through the atmosphere, to the hypothetical power density of the same signal if there were no atmosphere.



(a) Atmospheric transmittance vs. wavelength

(b) Atmospheric transmittance vs. zenith angle

FIG. 4 ATMOSPHERIC TRANSMITTANCE

of a laser beam impinging on a white target after having traversed 11.6 kilometers of atmosphere. Figure 6(a) shows an experimentally determined probability density function for the apparent atmospheric transmittance resulting from scintillation. A unity value of transmittance corresponds to a nonscintillating atmosphere. It is interesting to note that the expected reduction in signal amplitude due to scintillation is approximately one-half, and that reductions by a factor of 10 are not at all unlikely. In addition, since it is possible for a receiver to be located in a region of high intensity, effective values of transmittance greater than unity, indicating signal enhancement, are also possible. Figure 6(b) shows the power spectral density function of the signal intensity modulation due to scintillation.[6]

FIG. 5 BEAM PATTERN OF A RUBY LASER AT 11.6 km

The atmosphere causes a gross refraction of light coming to the earth from space since the mean refractive index of air differs from that of a vacuum. The extent of refractive bending is a function of the angle of incidence of the incoming ray measured with respect to the surface of the atmosphere; bending is minimum for perpendicular incidence and maximum for tangential incidence. The range of nominal mean values for atmospheric refraction is shown in Table I.[7] The actual value of atmospheric refraction experienced on any given day may vary by as much as 50% from the values shown, since the effective index of refraction of the atmosphere varies with temperature, barometric pressure, and other factors. Instrumentation is available, however, to accurately measure the effective atmospheric refraction

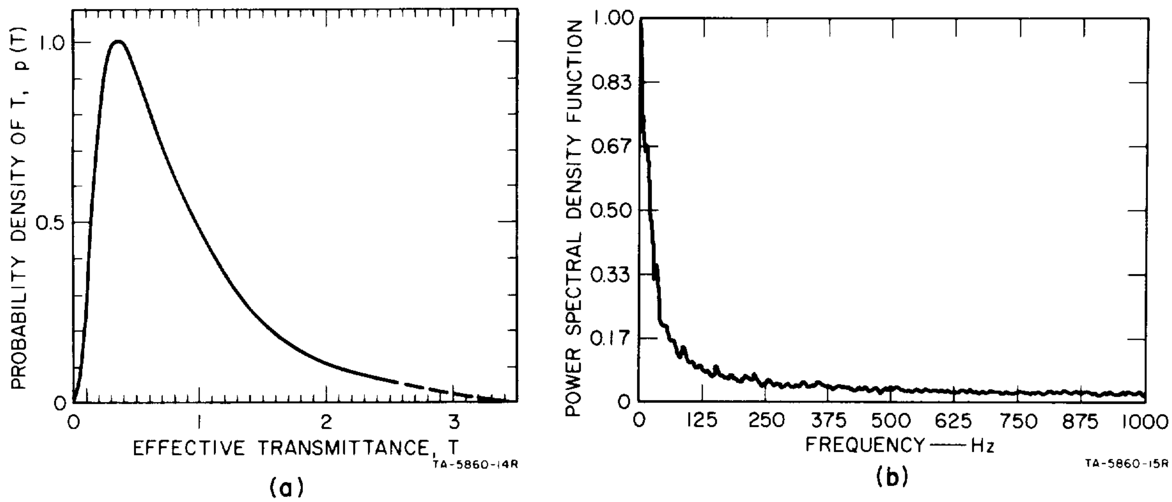


FIG. 6 EFFECT OF ATMOSPHERIC SCINTILLATION — 3-INCH APERTURE DIAMETER
(a) Probability density function of atmospheric transmittance
(b) Power-spectral-density function of atmospheric transmittance

at any given point and time. For pointing control purposes, therefore, the refractive bending of the atmosphere can be considered as a measurable parameter.

In addition to the steady-state refraction described above, the atmosphere causes a relatively rapid refractive bending about this steady-state value. This is manifested as rapid small-magnitude changes in the effective angle of arrival. When viewed at the focus of an astronomical telescope, this effect appears as jitter of the image formed by the telescope and has been given the name "image excursion" or "seeing" by astronomers. For normal atmospheric conditions, angle-of-arrival variations in the order of 1 to 5 seconds of arc can be expected, while variations as large as 15 to 30 seconds of arc have been observed under severe atmospheric turbulence. These variations occur at rates up to approximately 250 cycles per second with a peak in the vicinity of 13 cycles per second.[8]

The steady-state effects of atmospheric attenuation and refraction do not pose any serious problems in the design of a precision tracking or pointing system. Since the steady-state refraction can be accurately measured, this information can be supplied to

Table I

MEAN REFRACTION

(Corresponding to a temperature of 50°F, and a barometric pressure of 29.6 inches)

Elevation Angle	Refraction
0°	34'50"
1	24 22
2	18 06
3	14 13
4	11 37
5	9 45
6	8 23
7	7 19
8	6 29
9	5 49
10	5 16
11	4 47.7
12	4 24.5
13	4 04.4
14	3 47.0
16	3 18.2
18	2 55.5
20	2 37.0
22	2 21.6
24	2 08.6
26	1 57.6
28	1 48.0
30	1 39.5
35	1 22.1
40	1 08.6
45	57.6
50	48.3
55	40.3
60	33.2
65	26.8
70	20.9
80	10.2
90	0.0

the pointing control system and the effect compensated for. No similar compensation for attenuation is possible; hence, the system must be designed to operate successfully even during periods of maximum anticipated attenuation.

The direct effect of scintillation on a pointing or tracking system is to occasionally deteriorate the signal-to-noise ratio of the tracking-loop error signal. However, optimal estimation and control techniques, as described in Memorandum 7, permit the tracking system to be designed to minimize the deleterious effects of this occasional input-signal deterioration. On the other hand, the communication performance (in terms of signal-to-noise ratio) of the system will be drastically reduced during periods of signal fading. Many modern communication systems are designed to cope with this effect by reducing the transmitted information rate during periods of signal fade, thus making full use of the channel bandwidth available at any given instant. This technique, unfortunately, cannot be used to compensate for signal-amplitude variations due to scintillation, since the transit time inherent in communicating attenuation information from the receiver to the transmitter is greatly in excess of the correlation time of the scintillation-induced attenuation. Hence, the communication system must be designed to operate successfully not only in the face of the steady-state atmospheric attenuation, but in the presence of atmospheric scintillation as well. The effect of scintillation can be minimized by employing as large a receiver aperture as practical. If this aperture is much larger than the mean size of the bright and dark areas, the differing intensity levels will be averaged and the temporal variations reduced. This reduction is illustrated by the reduction in apparent twinkling of a distant light when viewed with a large-aperture telescope or binoculars as opposed to observation by the naked eye.

Image excursion due to atmospheric turbulence places several severe constraints on the design of the ground-based terminal of an optical communication system. Since, as a result of this effect, the signal arriving from a fixed point in space can appear to the receiver to be arriving from any direction contained within a 5-to-10-second cone about the true direction, the receiver must be designed to ensure that any such signal will be detected. One technique for ensuring detection is to design the receiver with a field of view larger than the anticipated cone of angle-of-arrival variations. This technique is simple, as it does not require any active elements. However, it suffers from the disadvantage that a wide-field-of-view receiver will collect more unwanted signal energy (background noise) and thus reduce the signal-to-noise ratio achievable at the receiving site. A second, more promising technique is to include a narrow-field-of-view, high-speed, small-angle tracking system in tandem with the normal telescope pointing system. This high-speed tracking system would then be capable of following the angle of arrival as it varies about its mean value. Angle-detection and beam-deflection techniques required to implement such a high-speed tracking system presently exist.

In the same way that an incoming signal is bent by the atmosphere, the signal from the ground-based transmitter is also bent. To ensure that the spacecraft is illuminated by the signal transmitted from earth, either the transmitter must radiate into a cone large enough to ensure illumination in spite of atmospheric refractions and pointing inaccuracies, or it will be necessary to steer the transmitted beam in such a way as to continuously ensure spacecraft illuminion. One technique for accomplishing transmitter beam steering is predicated on the fact that the atmosphere can be considered reciprocal over short periods of time. That is, a light beam transmitted from the ground to space along a path close to that of an incoming beam will be affected by the atmosphere in exactly the same manner as the incoming beam. When this is the case, transmitter beam steering can be accomplished by slaving the transmitter beam steerer to the high-speed receiver tracking system described above.

2. Free Space

There are two phenomena that affect the propagation of light through so-called "free" space. These are the relativistic interaction of light with a gravitational field, and the existence of regions of high ion density, principally clouds of free electrons.

The general theory of relativity states[9] that light, instead of traveling in a Euclidean straight line, follows the geodesics of a four-dimensional space-time field. In the absence of all masses the geodesics of this field would indeed be Euclidean straight lines. However, masses act to introduce curvature into the field and it is this curvature that causes the bending of a ray of light as it passes near a massive body. Since the mass-induced curvature is proportional to the mass and inversely proportional to the square of the distance separating the mass center and the light ray, the extent of the bending of a light ray can be inferred from observations of stars in the vicinity of the sun. It has been predicted, and experimentally verified, that a ray grazing the limb of the sun is deflected through an angle of 1.75 arc seconds. At 20 sun radii this bending is reduced to less than 0.005 arc seconds, a negligible amount with respect to the beamwidths and fields of view of optical systems within the forseeable future.

The radius of the sun is approximately 695,300 km;[10*] thus 20 sun radii is 13,906,000 km. Comparing this distance with the mean distance of 149×10^6 km between the earth and the sun, it is evident that bending due to the sun's mass will be completely negligible along any ray that does not pass within 0.1 rad (5.73 degrees) of the sun, and that it can be computed and compensated for in other cases. Considering the first six planets of the solar system, the ratio of their mass to the square of their radius, each expressed as a fraction of the corresponding quantity for the sun, provides a measure of the bending effect on a light ray grazing the limb of each planet. The values of this ratio are:

---

*All data in this paragraph is obtained from Ref. 10.

Mercury	0.0121
Venus	0.032
Earth	0.036
Mars	0.0132
Jupiter	0.090
Saturn	0.0375.

It is evident that only in the case of Jupiter will the bending be greater than 0.1 arc seconds, and in all cases a ray passing within several planet radii of the planet will be negligibly affected.

The refraction (or bending) of light traversing regions of high charge density is determined by application of Maxwell's equations. It can be shown that the angle through which the light beam will be bent is directly proportional to ion density and inversely proportional to the square of the optical signal's frequency.[11] In the ionosphere, where there are free electron densities on the order of 10^6 per cm^3, light beams, which have a frequency on the order of 10^{15} Hz, will be bent approximately 10^{-16} to 10^{-15} rad, depending on the signal's incident angle. In free space, where the expected ion densities are appreciably smaller than in the ionosphere, this bending will be much smaller. Therefore, the bending of optical beams induced by regions of high ion density is negligible for the systems being considered.

C. Implementation

Many of the techniques required for the implementation of an optical communication terminal are within the present state of the art and no significant technological advances are required to permit their immediate application. Included in this category are such items as astronomical telescopes, electro-optic tracking mounts, and short-wavelength quantum detectors. On the other hand, novel developments in the areas of optical axis measurement, beam steering, and heterodyne optical detection will considerably increase the capabilities of optical communications systems.

1. State-of-the-Art Techniques

The present quality of astronomical telescopes is such that the resolving power built into the telescope is far in excess of that actually realizable due to the distorting effects of the earth's atmosphere. The theoretical (diffraction limited) beamwidth is limited only by the telescope aperture diameter and the precision of the optical elements. The present technology for grinding lenses and reflectors permits sufficient accuracy that even the largest of astronomical telescopes (200-inch diameter) can be made capable of diffraction-limited operation in the absence of atmospheric aberrations. The design and fabrication techniques for telescope optics are therefore sufficiently developed to meet the demands of space communication.

Presently available electro-optical tracking mounts are capable of achieving steady-state pointing accuracy in the vicinity of one arc second and a small-angle tracking bandwidth in the order of 10 to 20 Hz. The digital angular readouts on the axes of these tracking mounts normally provide resolution in the vicinity of 1/4 to 1/2 arc second and accuracies of one arc second. While these capabilities are sufficient for the gross pointing of the major optics of a communication terminal, tracking mounts of this quality cannot be used alone if optical beamwidths on the order of 1/10 arc second or less are to be employed. For these cases an auxiliary, high-accuracy, high-speed system must be used in conjunction with a conventional tracking mount. Since it does not appear reasonable to expect either the accuracy or bandwidth of conventional mounts to be improved to the extent required by an optical communication system, a composite tracking system design provides the only workable solution for small optical beamwidths and high-frequency angle-of-arrival variations.

Of the presently available photodetectors, the types best suited for the detection of low-energy optical signals are those employing a photoemissive cathode, such as the photomultiplier tube and image orthicon. These, together with all present photodetectors, are quantum detectors in that they are sensitive only to incident energy and are not dependent for their operation on phase coherence of the incoming signal.[12] Some of the photomultiplier tubes, as well as the image orthicon, have the desirable property that the effective area of the photocathode is much smaller than the total cathode area. That is, the detector output signal is dependent on the optical power incident on only a small portion of the photocathode and is insensitive to power incident on other areas of the photocathode. Furthermore, this effective area can be electronically displaced to any position on the entire cathode area. Ratios of displacement range to effective area diameter in excess of 100 are easily obtainable. This scanning feature provides an easy means of implementation of the required small-angle, high-speed scanning capability for the communications receiver. Typical photoemissive devices exhibit an information bandwidth of at least several hundred megahertz. While this bandwidth may be sufficient in many applications, it does not approach the modulation bandwidth capabilities of an optical carrier.

The sensitivity of an optical receiver employing a photomultiplier detector is limited by the low quantum efficiency of the photocathode, which is typically on the order of 1% or less. This means that on the average only one of each 100 incident photons succeeds in causing the release of a photoelectron from the photocathode. Hence, the major portion of the incident optical energy is ignored by this detection process. A second limiting factor is the spontaneous emission by the photocathode of electrons in the absence of incident optical energy. This is caused by thermal agitation of electrons within the photoemissive cathode material. The rate of spurious emission can be substantially reduced by operation of the photocathode at cryogenic temperatures, but the effect cannot be completely eliminated and sets an ultimate limit on the sensitivity that can be achieved with a photoemissive device. The spectrum over which photoemissive detectors are useful is limited by the magnitude of the work function of photoemissive materials relative to the energy of an individual photon. Presently available photoemissive materials exhibit work functions such that only photons of wavelength less than approximately 1 micron have sufficient energy to result in photoelectron emission. Hence, photoemissive devices cannot be used to detect long-wavelength radiation (wavelengths greater than 1.0 microns). This is unfortunate since other considerations indicate that the region from 1.0 to 10 microns may be a desirable portion of the spectrum within which to operate an optical communication system.

2. Novel Techniques

In order to enhance the operational capabilities of an optical communication system it is highly desirable that improved techniques be developed in such areas as optical axis measurement, beam steering, and coherent optical detection. A key problem in the obtaining of angle tracking data from an optical tracking system is the determination of the instantaneous optical axis of the tracking system. Present techniques for measuring the pointing angles of the optical axis involve the measurement of the angles of the mechanical axis of the tracking telescope by means of digital angle encoders, and is based on the assumption that the optical and mechanical axes coincide. As was pointed out above, the mechanical telescope axis angular position can seldom be determined with an accuracy to better than 1/2 second of arc. Since this error is larger than the anticipated beamwidths, it is evident that more accurate measurement techniques are required. One possible approach to this problem is the direct measurement of the optical axis by means of reflective or interference techniques so that the angular position of the optical axis can be directly measured relative to stationary reference points independent of the tracking mount.

Several techniques have been investigated for realizing small-angle, high-frequency steering of an optical beam. These techniques include electro-optic cells, such as KTN, and piezoelectric crystal mirrors. In the context of an optical communication system, it would be desirable to develop methods for utilizing beam-steering techniques such that the accuracy of the resultant beam-steering system is not dependent upon the accuracy with which the position of the optical beam can be measured--for example, if the angle of deflection generated by the beam steerer is controlled via feedback from the optical detection device. In this case, the calibration of neither the optical detector nor the beam steerer need be accurately known to realize accurate tracking. Similarly, if steering of a transmitting beam is required it would be desirable that the same beam steerer be used to steer both the receiving and transmitting beams, thereby insuring that the transmitted beam accurately follows the path of the received beam. For those cases where a point-ahead angle must be incorporated in the transmitted beam, this angle should be inserted by a separate beam steerer so that any calibration errors of this beam steerer effect only the point-ahead angle and not the absolute pointing angle.

With the availability of coherent laser light sources for use as transmitters and local oscillators, it is now possible to consider the heterodyne detection of an optical signal to achieve the maximum possible utilization of signal energy collected by the receiving aperture. Due to the turbulent effects of the atmosphere, heterodyne detection at visible wavelengths would be limited to effective apertures of at most a few inches diameter and, hence, would have to operate at extremely small input signal levels although a technique has been suggested for overcoming this limitation.[13] The coherence aperture at a wavelength of 10 microns, however, is in the order of 3 to 4 meters, thus allowing coherent detection using collecting telescope apertures of significant size. A further advantage of coherent detection is the possibility of extremely large communication-channel bandwidth since microwave diodes or solid-state photodiodes with bandwidths exceeding several gigahertz can now be used to detect the intermediate frequency signal. Experiments are presently being planned at the GSFC to test and evaluate the coherent detection of a laser signal after reflection from an earth satellite.[14]

III SYSTEM EVALUATION

To permit a complete study of the capabilities and performance of an optical communication system, and in particular to evaluate suggested techniques for achieving the high-precision pointing required, it has been decided to simulate in detail the two terminals and the propagation path of such a system. This simulation will be carried out on a digital computer and is a natural extension of previous work, described in Memorandum 7, in which the problem of high-precision tracking of space vehicles by large radio antennas was investigated. A feature of both the previous and present simulations is the incorporation of state estimation and optimum control functions designed on the basis of optimal estimation and control theory.

The cooperative system configuration, as described in Sec. II-A, has been chosen for this stimulation since it appears at present to be the most promising candidate for an actual system design. The final program will include simulations of the dynamics of both the earth-based terminal and the spacecraft-borne terminal, as well as the properties of the intervening space and atmosphere. The earth-based terminal will be modeled first; the description of the spacecraft terminal will be treated at a later date. A detailed discussion of the structure and elements composing the earth-based terminal is presented in the following sections; the specific mathematical descriptions and numerical values will be presented in Memorandum 9.

A. Structure of Earth-Based Terminal

The individual components of the earth-based terminal of a cooperative communication system, together with the definition of the important system variables are illustrated in Fig. 7. The terminal is designed to perform the following two basic functions:

(1) Track the laser signal transmitted from the spacecraft in order to orient the receiver

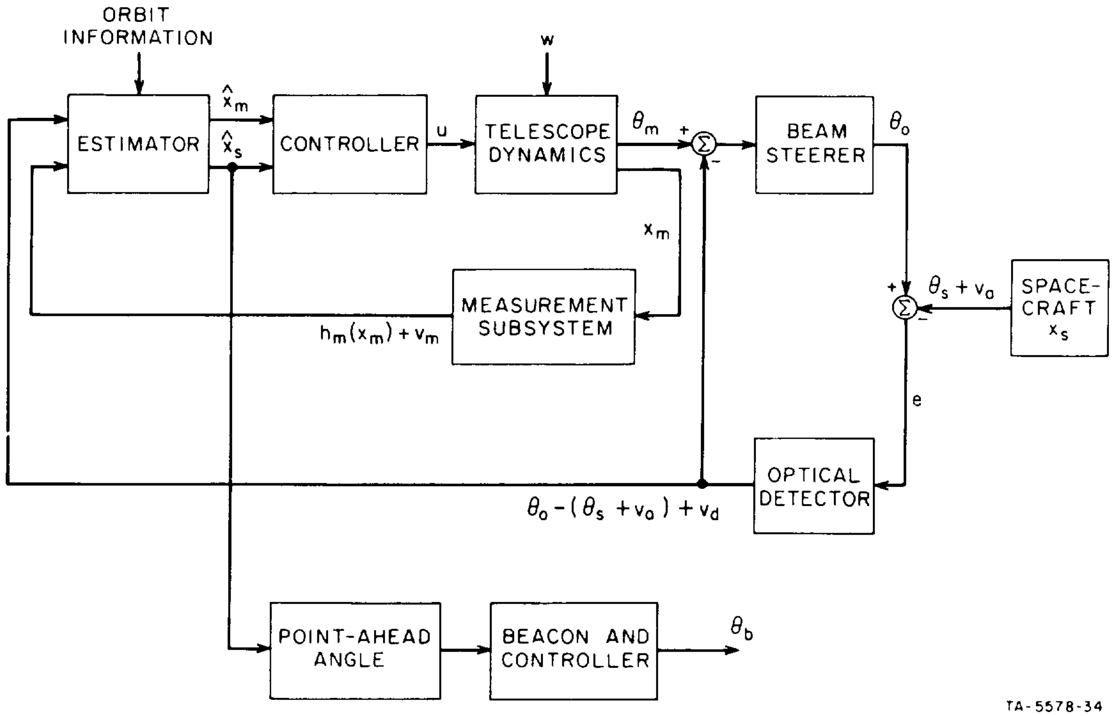


FIG. 7 STRUCTURE OF EARTH-BASED TERMINAL

axis to maintain a high signal-to-noise ratio

(2) Compute the point-ahead angle for aiming the beacon, which is tracked by the spacecraft and used by it for spacecraft orientation.

The angle of arrival of the incoming optical signal that is to be tracked by the receiver is defined by the relative motion of the spacecraft with respect to the tracking site.

The spacecraft state can be described by the six-dimensional vector x_s, comprised of three position components and the corresponding three velocity components. The motion of the spacecraft is described by the nonlinear differential equation

$$\dot{x}_s = f_s(x_s, t) \tag{1}$$

where the explicit time dependence represents the random perturbations (e.g., micrometeorites) that influence the flight path of the spacecraft.

The angle of arrival of the signal transmitted from the spacecraft is denoted by $\theta_s + v_a$. θ_s represents the angle of arrival that would result if the geometric line of sight were unperturbed; v_a represents the perturbations, such as refraction and image excursion, that cause the angle of arrival to differ from θ_s. The angle θ_s is a nonlinear function of the state x_s--i.e.,

$$\theta_s = h_s(x_s, t) \tag{2}$$

where the explicit time dependence results from the motion of the earth in its orbit and the earth's rotation about its axis.

The optical detector, which is assumed to be a scanned photomultiplier, directly measures e, the angular difference between the angular orientation of the optical axis (θ_o) and the angle of arrival ($\theta_s + v_a$). This measurement is corrupted by measurement noise v_d, due to calibration errors, readout errors, and resolution errors.

The dynamics of the receiver telescope, including the drive motors, are described by the state vector x_m which represents the behavior of the receiver's mechanical axis (θ_m). The term w represents random perturbations acting upon the telescope system, such as wind disturbances, while the control variable u represents the telescope drive system input signals. Because the state of the telescope system is not directly measurable, those measurements that are obtainable are represented as a function $h_m(x_m)$ of the telescope state, and these measurements will be corrupted by measurement noise and errors represented by v_m.

The receiver tracking system is composed of two tracking loops operating in series. The primary loop contains the estimator, controller, telescope mechanical axis, and telescope measurement subsystem. The function of the primary loop is to provide smooth tracking of the slowly varying mean value of the incoming signal angle of arrival as well as to produce optimal estimates of the state of the spacecraft, and to accomplish both of these tasks in spite of the measurement disturbances introduced by atmospheric effects. By providing smooth tracking of the angle-of-arrival mean value, the instantaneous angle of arrival will be kept within the dynamic range of the beam steerer. The secondary tracking loop is a direct feedback of the optical detector output, $e = \theta_o - (\theta_s + v_a)$, to a high-speed beam steerer. The purpose of this secondary tracking loop is to cause the receiver optical axis to follow the rapid fluctuations in signal angle of arrival, thus ensuring maximum possible receiver signal-to-noise ratio at all times. Present thinking indicates that the beam steerer can best be implemented by a system of piezoelectrically rotated mirrors, and this configuration will be incorporated into the initial simulation.

The estimator processes the noise-corrupted data to generate estimates of the states of the spacecraft and telescope, x_s and x_m, respectively. Other data, such as orbit and ephemeris information, can be incorporated into the estimator to improve these estimates. The estimates are employed in the controller, where a control signal u is calculated to minimize a specified tracking performance criterion. The control u causes the telescope mechanical axis to track the deterministic, slowly varying component of the signal's angle of arrival. Having the incoming signal thus kept within its dynamic range, the beam steerer causes the optical axis to track the stochastic, rapidly changing component of the angle of arrival by nulling the error signal e.

The estimate of spacecraft state provided by the estimator within the tracking system is used as the input data for computing the pointing angles of the terminal's beacon transmitter. Since the beacon transmitter pointing angles will be close to those of the receiver (a maximum of 3 to 4 arc minutes difference for a mars mission), the same telescope can be used for both transmitter and receiver, and the transmitter point-ahead angles computed as offsets from the receiver optical axis.

Two effects contribute to the point-ahead angle: velocity (Bradley) aberration, and transit (propagation) time. The velocity aberration is a relativistic effect, which is a function of the relative velocity between the spacecraft and the ground-based station.[16] Hence, this contribution to the point-ahead angle, which is typically less than 20 to 30 arc seconds can be computed and compensated for.

A nonzero transit time results from the finite velocity of light--i.e., there is a delay between the time a signal is transmitted and when it is received. For a typical Earth-Mars mission, involving distances for communication on the order of 3×10^8 km, the one-way transit time τ is approximately 16 min. Thus, the contribution to the point-ahead angle due to transit time is calculated by performing a prediction over 2τ units of time (τ units of time for the signal transmitted from the spacecraft to have reached the receiver, plus τ units of time until the signal sent by the beacon will illuminate the spacecraft). The prediction can be obtained by using $\hat{x}_s$, the estimate of the spacecraft state, as an initial condition in the equations of motion (1), integrating over 2τ, and then substituting this result into Eq. (2). The accuracy of this prediction is dependent on the model for the equations of motion and the accuracy of the estimate $\hat{x}_s$. The beacon transmitter optical axis θ_b is offset from the receiver optical axis by the point-ahead angle as calculated from these two effects.

B. Modeling of Tracking System Components

To formulate the system simulation in a rigorous manner it is necessary to develop mathematical models for the various elements of the system shown in Fig. 7. Memorandum 9, which is being prepared as a sequel to this memorandum, will discuss the models for the earth-based terminal of a cooperative system in detail, giving the functional form for each model and explicit numerical values for the system parameters.

The dynamic behavior of the telescope and of its drive motors can be approximated in each case by a set of linear differential equations. The assumption of linearity is quite reasonable for normal tracking operation since the tracking-loop signals (rates and displacements) will be small. Since the bandwidth of the beam steerer is considerably greater than the effective closed-loop bandwidth of the primary tracking loop, the components of the secondary tracking loop (the optical detector and the beam steerer) can be considered to have no dynamics and therefore be described by simple algebraic equations.

The wind disturbance w and the measurement noises v_d, v_a, and v_m contain components that are stochastic in nature.[17] Hence, these perturbations must be described by a sufficient set of statistics. When the random process is gaussian, it can be completely characterized by its mean, covariance, and power spectral density. In the case of nongaussian processes, an approximate description in terms of these quantities may be appropriate. The deterministic components of the measurement noises can be evaluated and compensated for within the general framework of the problem.

With the simulation formulated in this manner, linear optimal estimation and control theory can be applied to derive the equations for the estimator and controller. Application of the linear theory will necessitate the linearization of the equations of motion for the spacecraft and some of the measurement equations. This approach has proven very successful for the problem of tracking spacecraft with large radio antennas, which is described in Memorandum 7.

IV CONCLUSIONS

As a result of this investigation it can be concluded that optical communication systems do indeed promise a significant increase in communication capability over interplanetary distances. Furthermore, much of the technology and many of the devices required to implement an optical communication system are within the existing state of the art. Those areas where development is needed are already being investigated and no fundamental limitation appears to preclude significant advances.

Of the three classes of system configuration studied, the cooperative technique offers the most attractive possibilities, and of the three, it appears to yield the greatest system capability and performance for the amount of equipment and complexity involved. For this reason the cooperative system configuration has been chosen as the subject of an intensive study and simulation throughout the remainder of the project.

For a communication system where one terminal is located on the earth's surface, the principal factor degrading the ideal system performance will be the perturbations of the optical path introduced by the earth's atmosphere. The nature of atmospheric interference is well enough known to anticipate its gross deleterious effects; however considerably more atmospheric research, using all of the advanced optical and satellite technology available, should be done to discover all of the detailed mechanisms at work within the atmosphere and possibly develop techniques for nullifying their effects on optical transmission.

To avoid atmospheric disturbances, both terminals could be located in space, the one nearest earth (e.g., an earth-orbiting satellite) using a second link to relay information down to the earth's surface. In this case the system performance will be limited by two factors: (1) the degree to which spacecraft can be stabilized and reference systems defined, and (2) the uncertainties in the orbital mechanics of the spacecraft, the planets within the solar system, and the motion of the entire solar system with respect to the stars. Orbiting astronomical observatories will undoubtedly contribute to the reduction of these uncertainties. The nature of these two factors--spacecraft stabilization and orbital mechanics uncertainty--will be discussed in detail in a future memorandum, when the design of the spacecraft-borne terminal of the cooperative optical communication system is considered.

While such devices as astronomical telescopes and quantum detectors have been developed to a high degree of precision, existing electro-optical tracking mounts and optical axis measurement techniques do not meet the stringent requirements of an optical communication system. Developments will be required in these areas, or systems designed so as to relax the demands on these components, if maximum system performance is to be achieved. Furthermore, the continued development of optical heterodyne detection as an alternative to quantum detection will lead to the realization of the ultimate in detector sensitivity, with a corresponding increase in communication-channel capacity.

REFERENCES

1. R. M. Dressler, "Application of Optimum Estimation and Control Theory to Satellite Tracking Problems," Memorandum 7, SRI Project 5578, Contract NAS 12-59, Stanford Research Institute, Menlo Park, California (6 April 1966).

2. J. G. Truxal, Control System Synthesis, Chapter 9 (McGraw Hill Book Co., Inc., New York, New York, 1955).

3. R. E. Kalman, "A New Approach to Linear Filtering and Prediction Problems," Trans. ASME, J. Basic Engineering, pp. 35-45 (March 1960).

4. "Lasers and Their Applications," Conference sponsored by IEE Electronics and Science Divisions, 1964.

5. M. Ross, Laser Receivers, Chapter 8 (John Wiley and Sons, New York, New York, 1966).

6. K. W. Gardiner, et al., "Direct Fire Simulation System," Final Report, SRI Project 5860, Contract DA-04-200 AMC-1884(X), Stanford Research Institute, Menlo Park, California (October 1966).

7. H. N. Russell, R. S. Dugan, and S. Q. Stewart, Astronomy (Ginn & Co., New York, New York, 1926).

8. Private communication--H. H. Plotkin, et al., Optical Systems Branch, NASA, Goddard Space Flight Center, Greenbelt, Maryland, October 1966.

9. R. M. Besancon, Ed., Encyclopedia of Physics (Reinhold, New York, New York, 1966).

10. C. D. Hodgman, Ed., Handbook of Chemistry and Physics, p. 3086 (Chemical Rubber Publishing Company, Cleveland, Ohio, 1953).

11. G. P. Harnwell, Principles of Electricity and Electromagnetism, Chapter 16 (McGraw Hill Book Co., Inc., New York, New York, 1949).

12. "Multiplier Phototubes," Allen B. DuMont Laboratories, Inc., Clifton, New Jersey (1959).

13. A. Macovski and W. Barnes, "Optical Heterodyne Detection," Internal Research Memorandum, Stanford Research Institute, Menlo Park, California (15 February 1965).

14. N. McAvoy, "10.6 Micron Communication System," Technical Report No. X-524-65-461, NASA Goddard Space Flight Center, Greenbelt, Maryland (November 1965).

15. L. Meier, "Combined Optimum Control and Estimation Theory," Contractor Report, SRI Project 5237, Contract NAS 2-2457, Stanford Research Institute, Menlo Park, California (October 1965).

16. F. A. Jenkins and H. E. White, Fundamentals of Optics (McGraw Hill Book Co., Inc., New York, New York, 1950).

17. G. C. Newton, L. A. Gould, and J. F. Kaiser, Analytical Design of Linear Feedback Controls (John Wiley and Sons, Inc., New York, New York, 1957).

Appendix A

NUMERICAL EXAMPLE

Appendix A

NUMERICAL EXAMPLE

The purpose of the numerical example presented in this appendix is to illustrate that the concept of optical communication between sites separated by large distances is indeed feasible. It is not intended to be representative of any particular system configuration, nor are the assumptions made regarding wavelength, power, etc., indicative of any particular device. The only intent here is to show that for parameter values that are either already within the state of the art, or can reasonably be expected to be so within the next several years, significant channel capacity can be achieved via optical techniques at interplanetary distances.

1. Spacecraft to Earth (Down-Link)

a. Signal Power

Assume that the spacecraft if equipped with a 1-meter-diameter telescope and a 10-watt-output laser operating at a wavelength of 1.0 microns. The diffraction-limited beamwidth (to the 3-dB points) is

$$BW = 1.2 \frac{\lambda}{d}$$

$$= 1.2 \times 10^{-6} \text{ radians} \quad .$$

Due to the requirement that the ground station be continuously illuminated, in spite of atmospheric bending effects, it is necessary to illuminate an area larger than the receiver aperture. The extent of this area can be determined by assuming that under good seeing conditions an incoming ray will not be bent away from its steady-state position by more than 5 seconds of arc. By projecting a cone with a 10-arc-second apex angle located at the receiving site to the upper surface of the atmosphere, assumed to be at an altitude of 100 km, a circle with a diameter of 5 meters is obtained. This circle contains all the points from which radiation received on the earth's surface would appear to come. Since a beamwidth of 1.2×10^{-6} radians at a distance of 2×10^{11} meters (nominal distance for a Mars mission) illuminates a circle 2.4×10^{5} meters diameter, there is no problem of insuring continuous site illumination.

The power density at the earth site resulting from the spacecraft transmitter is given by

$$P = \frac{4\, P_T\, A_T\, A_a}{\pi\, \alpha^2\, r^2} \qquad \text{watts/meter}^2$$

where

P_T = Transmitter power

A_T = Transmittance of transmitter optics

A_a = Atmospheric transmittance

α = Transmitter beam divergence

r = Range.

Taking as representative values

P_T = 10 watts

A_T = 0.8

A_a = 0.1 (including the effects of attenuation and scintillation)

$\alpha = 1.2 \times 10^{-6}$ radians

$r = 2 \times 10^{11}$ meters

this power density becomes

$$P = \frac{4 \times 10 \times 0.8 \times 0.1}{\pi \times 1.44 \times 10^{-12} \times 4 \times 10^{22}}$$

$$= 1.77 \times 10^{-11} \qquad \text{watts/meter}^2 \quad .$$

Assuming that the receiving site utilizes a telescope with a 5-meter collecting aperture (approximately equivalent to the 200-inch Palomar telescope), and an optical efficiency of 80%, the received signal power is found from

$$P_{RS} = P(0.25\ \pi\ d^2)\ A_R$$

$$= 1.77 \times 10^{-11} \times 0.25 \times 3.14 \times 25 \times 0.8$$

$$= 2.78 \times 10^{-10} \quad \text{watts} \quad .$$

For a 1.0-micron wavelength, this power corresponds to an average photon rate of

$$N_{RS} = \frac{P_{RS}\ \lambda}{h\ c}$$

where

c = Velocity of light = 3×10^8 m/s

h = Planck's constant = 6.624×10^{-34} watt s^2

λ = Wavelength = 10^{-6} meters.

For these values,

$$N_{RS} = \frac{2.78 \times 10^{-10} \times 10^{-6}}{6.624 \times 10^{-34} \times 3 \times 10^8}$$

$$= 1.4 \times 10^9 \quad \text{photons/s} \quad .$$

b. Background Power

If the ground receiver site is to operate during daylight hours, the predominant source of background radiation (excluding direct viewing of the sun) will be the bright clear sky. This can be considered as a distributed source with an irradiance at 1 micron of 65 watts/meter^2 steradian micron. Assuming an optical filter of 10^{-4} micron

bandwidth, and the diffraction-limited beamwidth of 0.24×10^{-6} radians,*
the received background power is

$$P_{RB} = R_B \; (0.0625 \; \pi^2 \; d^2 \; \alpha^2) \; B$$

$$= 65 \times 0.0625 \times 9.86 \times 25 \times 0.0576 \times 10^{-12} \times 10^{-4}$$

$$= 5.77 \times 10^{-15} \quad \text{watts}$$

which corresponds to an average photon rate of

$$N_{RB} = 2.9 \times 10^4 \quad \text{photons/s} \quad .$$

c. Channel Capacity

Assume that a photomultiplier is used to detect the signal and that an average signal-to-noise ratio of 10 is required for reliable communication. The photocathode of a photomultiplier emits spurious photoelectrons even when no photons are impinging on the photosensitive surface. This electron flow is referred to as dark current and can be expressed as a noise effective power (NEP)--the optical power required to produce the same cathode current. For a cooled S1 (infrared-sensitive) cathode this NEP is in the order of 10^{-14} watts and corresponds to a photon arrival rate of

$$N_{RD} = 5.02 \times 10^4 \quad \text{photons/s} \quad .$$

---

*A telescope located on the earth can rarely be operated diffraction-limited for two reasons--image excursion and image spreading. The first of these is the predominant disturbance and is manifested as a wandering of the image in the focal plane resulting from time variation of the apparent angle of arrival. This effect can be compensated by high-speed following of the image. Image spreading results from multipath effects across the telescope aperture--that is, the simultaneous existence of more than one apparent angle of arrival. At present there is no known way to compensate for this effect in large-aperture telescopes. For simplicity here, however, diffraction-limited operation is assumed.

The maximum channel bandwidth for a given signal-to-noise ratio can be obtained from the expression

$$\Delta f = \frac{\nu N_{RS}}{2H \left(\frac{S}{N}\right)^2 \left(1 + \frac{N_{RB} + N_{RD}}{N_{RS}}\right)}$$

where

Δf = Bandwidth in cps

ν = Photocathode quantum efficiency = 0.01

H = Photomultiplier noise figure = 1.25

$\frac{S}{N}$ = Signal-to-noise ratio = 10.

For these values,

$$\Delta f = \frac{0.01 \times 1.4 \times 10^9}{2 \times 1.25 \times 100 \times \left(1 + \frac{2.9 \times 10^4 \times 5.02 \times 10^4}{1.4 \times 10^9}\right)}$$

$$= 5.6 \times 10^4 \text{ cps} \quad .$$

A channel of bandwidth Δf has a 95% rise time of approximately

$$\tau = \frac{3}{2\pi \, \Delta f}$$

which, for the above channel bandwidth, is

$$\tau = \frac{3}{6.28 \times 5.6 \times 10^4}$$

$$= 8.55 \times 10^{-6} \text{ seconds} \quad .$$

Taking one rise time and one fall time as the time required to transmit one bit, the net channel capacity is therefore

$$C = \frac{1}{2\tau}$$

$$= 5.85 \times 10^4 \text{ bits/second} \quad .$$

2. Earth to Spacecraft (Up-Link)

For convenience, again assume operation at a wavelength of 1.0 micron, although in practice the up-link and down-link frequencies would have to be different to permit discrimination within common optical systems.

a. Signal Power

Although a large-aperture transmitter, with corresponding narrow beamwidth, is feasible to mechanically operate on the Earth's surface, uncertainties in the atmospheric path dictate that a somewhat larger beam be used to insure illumination of the spacecraft. Therefore assume that an up-link beamwidth of 5×10^{-6} radians is used. The signal power density in the vicinity of the spacecraft is then

$$P = \frac{4P_T A_T A_a}{\pi\alpha^2 r^2} \quad \text{watts/meter}^2 \quad .$$

Taking as representative values,

$P_T = 100$ watts

$A_T = 0.8$

$A_a = 0.1$ (including attenuation and scintillation)

$\alpha = 5 \times 10^{-6}$ radians

$r = 2 \times 10^{11}$ meters,

then

$$P = \frac{4 \times 100 \times 0.8 \times 0.1}{3.14 \times 25 \times 10^{-12} \times 4 \times 10^{22}}$$

$$= 1.02 \times 10^{-11} \quad \text{watts/meter}^2 \quad .$$

The received power collected by the 1-meter on-board aperture is then

$$P_{RS} = P\,(0.25\,\pi\, d^2)\, A_R$$

and assuming an optical efficiency of 80%,

$$P_{RS} = 1.02 \times 10^{-11} \times 0.25 \times 3.14 \times 1 \times 0.8$$

$$= 6.4 \times 10^{-12} \quad \text{watts} \quad .$$

The corresponding average photon rate is

$$N_{RS} = 3.22 \times 10^{7} \quad \text{photons/s} \quad .$$

b. Background Power

The significant background radiation received by the spacecraft receiver will be sunlight reflected from the Earth's surface. If the Earth is assumed to be a uniform diffuse reflector with an albedo of 0.4, then its irradiance at 1 micron is 143 watts/meter^2 steradian micron. Again assuming a 10^{-4} micron optical filter, the background power collected by the spacecraft receiver is given by

$$P_{RB} = R_B \; (0.0625 \; \pi^2 \; d^2 \; \alpha^2) \; B$$

$$= 143 \times 0.0625 \times 9.86 \times 1 \times 1.44 \times 10^{-12} \times 10^{-4}$$

$$= 1.27 \times 10^{-14} \quad \text{watts}$$

which corresponds to an average photon rate of

$$N_{RB} = 6.37 \times 10^{7} \quad \text{photons/s} \quad .$$

c. Channel Capacity

Assuming (1) that a photomultiplier is again used to detect the signal, and (2) in this case taking the NEP to be 10^{-13} watts since, in space, the photocathode is not shielded by the atmosphere and is thus subject to high-energy particle bombardment which results in increased spurious electron emission, the effective background power due to dark current is

$$P_{RD} = 1.0 \times 10^{-13} \quad \text{watts}$$

and the corresponding photon rate is

$$N_{RD} = 5.02 \times 10^{5} \quad \text{photons/s} \quad .$$

Again requiring an average signal-to-noise ratio of 10 yields an up-link channel bandwidth of

$$\Delta f = \frac{\nu N_{RS}}{2H \left(\frac{S}{N}\right)^2 \left(1 + \frac{N_{RB} + N_{RD}}{N_{RS}}\right)}$$

$$= \frac{0.01 \times 3.22 \times 10^{7}}{2 \times 1.25 \times 100 \times \left(1 + \frac{6.37 \times 10^{4} + 5.02 \times 10^{5}}{3.22 \times 10^{7}}\right)}$$

$$= 1.26 \times 10^{3} \quad \text{cps}$$

and a corresponding capacity of

$$C = 1.32 \times 10^{3} \quad \text{bits/s} \quad .$$

While the channel capacities indicated in this example represent significant improvement over that presently achievable by microwave techniques, they by no means represent full exploitation of optical capabilities. Future development of coherent detection techniques and higher-power sources should increase these channel capacities by at least one order of magnitude. The values obtained in this example are indicative of the performance that can be achieved with the present state of the art.

Appendix B

GLOSSARY OF TERMS

Appendix B

GLOSSARY OF TERMS

1. Accuracy--The term accuracy is used to describe the fidelity with which the output of a system or device responds to the input. The accuracy of a measurement system indicates how closely the output signal corresponds to the value of the quantity being measured. Conversely, for an actuator, accuracy implies how closely the output position (or other property) corresponds to the position commanded by the input signal. For example, pointing accuracy means how closely the axis angles of a telescope align with the commanded angular values.

2. Acquisition--Acquisition refers to that phase in the operation of a system when the terminals are initially making contact with each other--or re-establishing contact following some interruption. Since the uncertainties in the *a priori* information and measurements available will most likely exceed the normal operating range of the system, provision must be made to modify the system structure to ensure establishment of contact despite these uncertainties. While operating thus modified, the system is said to be in the acquisition mode. Once contact has been established between the two terminals, systematic transition from the acquisition mode to the operational mode can be effected.

3. Albedo--The albedo of a diffusely reflecting surface is the ratio of the intensity of the light reflected normal to the surface, to the incident light intensity.

4. Beam Steering--Beam steering refers to the technique of displacing the effective field of view (radiation pattern) of a telescope without moving the telescope itself. This can be done either by translation of the detector (light source) in the focal plane of the telescope, or by bending the optical path between the telescope

aperture and focal plane. For convenience this bending would be introduced in front of, but close to, the focal plane, where the beam diameter is small. This permits the use of small beam-deflection devices, but on the other hand restricts the dynamic range.

5. Beamwidth--The beamwidth of a radiation pattern is defined as the angle about the central axis at which the radiated power density is one half the power density on the central axis. Since, for all systems considered, circular symmetry exists, the beamwidth is independent of the plane in which it is measured.

6. Channel Capacity--The capacity of a communication channel is defined as the number of bits of information that can be transmitted over it with a given probability of error for each bit. Although the channel capacity of a system has been calculated in many ways, the following is the method that will be used throughout this project: The probability of error can be derived as a function of the detection process and the receiver signal-to-noise ratio. It is assumed that for any detection process to be used, a signal-to-noise ratio of 10 will lead to acceptably low error probabilities. From the calculated signal power available and the signal-to-noise ratio, the allowable noise power is determined. Since the system noise can be assumed to be uniformly distributed in frequency (white), the allowable noise power directly dictates the allowable system bandwidth Δf. A bandwidth Δf corresponds to a system rise-time-constant of $\frac{1}{2\pi\Delta f}$. In order to ensure adequate system response, the bit length is taken equal to 3 time constants, and since the system must both rise and recover for each bit (unless a non-return-to-zero code is employed), the time to transmit one bit becomes 6 time constants. Thus the channel capacity C, in bits per second, is related to the channel bandwidth by

$$C = \frac{2\pi}{6} \Delta f \quad .$$

7. Diffraction-Limited--The term diffraction-limited applies to the operation of an optical instrument where performance is limited by the physical phenomenon of optical diffraction rather than disturbances arising from the intervening transmission path (such as the atmosphere) or imperfections in the construction of the optical instrument itself. The phenomenon of diffraction gives rise to the fact that an instrument with an aperture diameter d cannot produce a beamwidth smaller than θ. For a circular, uniformly illuminated aperture the relationship is $\theta = 1.22 \frac{\lambda}{d}$ (rad), where λ is the wavelength of the illuminating light. In the case of a receiver, diffraction limits the minimum size of the image that can be formed in the focal plane and hence limits the smallest resolution angle that can be achieved to an angle θ that is identical to that for the transmitted beamwidth.

8. Field of View--The field of view of a receiving telescope is defined as the angle about the central axis at which the power sensitivity is one-half the axial value. In most cases the field of view will be defined by a field-stop aperture located in the telescope focal plane. The field of view θ is then given by $\frac{d}{f}$ (rad), where d is the field-stop diameter and f is the telescope focal length. There is no point in making the field-stop diameter smaller than the diffraction-limited image size, since to do so would exclude from the detector a portion of the signal energy collected by the telescope receiving aperture.

9. Limb--When viewed through a telescope, nearly all celestial bodies appear as disks. The limb of a celestial body is the rim of this apparent disk.

10. Resolution--The resolution (or precision) of a measuring device is an indication of its inherent quantization level--that is, the amount of change that must occur in the input before a detectable change occurs in the output. For example, a 21-bit shaft angle encoder exhibits a resolution of 0.618 arc seconds. However, if this encoder were bolted to the shaft incorrectly, its accuracy would be orders of magnitude worse than this resolution figure.

11. Tracking--The word tracking is commonly used to mean three different things: point, following, and data collection. Each of these terms will be defined here; which definition is implied in any given usage should be clear from the context.

Pointing--Pointing implies the orienting of the telescope axis on the basis of input information derived from a source other than the telescope itself. For example, if the input signals to the telescope-drive servos are derived from orbit-prediction data, and no data on the error between the telescope axis and the desired direction given by the inputs is fed back, this mode of operation is called pointing.

Following--In contrast to pointing, following implies that the input drive signals are derived, at least in part, from the error between the telescope axis and the desired direction. The function of a following system is to continually reduce this error to zero--that is, to seek a null error condition. Following is directly analogous to the "auto-track" mode commonly employed in radar.

Data Collection--Tracking for the purpose of data collection implies that the objective is a record of the angular position of the target (other terminal) relative to the tracking site as a function of time. To accomplish this end, the usual procedure is to maintain contact with the target by means of following, and record as functions of time the angular orientation of the telescope axis. A sharp distinction is made here between the two operating modes, following and data collection, since data collection involves an absolute measurement whereas following involves only the nulling of error signals. As a result, following can in many cases be carried out very accurately--that is, the telescope axis will very closely coincide with the direction of the incoming signal, whereas limited capability to measure the position of the telescope axis will restrict the data collection operation to only moderate accuracy. To illustrate this distinction consider an optical communication terminal with a 0.1-arc-second field of view. If following is performed very well, then maximum signal strength will be continually maintained and the communication function will be successful. If, on the other hand, the position of the optical axis can be measured with an accuracy of only 10 arc seconds, then the data-collection function falls two orders of magnitude short of the accuracy being achieved by the following system.